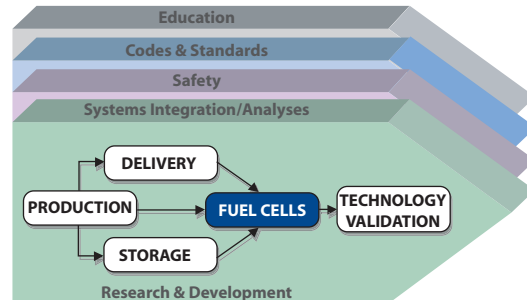## 3.4 Fuel Cells

Fuel cells have the potential to replace the internal combustion engine in vehicles and to provide power in stationary and portable power applications because they are energy-efficient, clean, and fuel-flexible. Hydrogen or any hydrogen-rich fuel can be used by this emerging technology. For transportation propulsion applications, DOE is focusing on direct hydrogen fuel cells, in which on-board storage of hydrogen is supplied by a hydrogen generation, delivery, and fueling infrastructure. This infrastructure is being developed in parallel with the fuel cell development efforts. Another technology supported by the Fuel Cell program element is on-board fuel processing, in which fuels supplied by existing infrastructure, such as gasoline, methanol, ethanol, natural gas, or other hydrocarbon fuel can be processed on-board the vehicle to supply hydrogen. For distributed generation fuel cell applications, the program focuses on near-term fuel cell systems running on natural gas or propane and recognizes the longer term potential for systems running on renewable fuels. Auxiliary power systems are expected to use diesel or propane for truck applications and possibly propane for recreational vehicles. Small consumer electronics systems will probably use hydrogen or methanol.

3.4.1 Technical Goal and Objectives

Goal

Develop and demonstrate fuel cell power system technologies for transportation, stationary, and portable applications.

Objectives

- Develop a 60% efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $45/kW (including hydrogen storage) by 2010 and $30/kW by 2015.

- Develop a 45% efficient reformer-based fuel cell power system for transportation operating on clean hydrocarbon or alcohol-based fuel that meets emissions standards, a startup time of 30 seconds, and a projected manufactured cost of $45/kW by 2010 and $30/kW by 2015.

- Develop a distributed generation PEM fuel cell system operating on natural gas or propane that achieves 40% electrical efficiency and 40,000 hours durability at $400-$750/kW by 2010.

- Develop a fuel cell system for consumer electronics with an energy density of 1,000 Wh/L by 2010.

- Develop a fuel cell system for auxiliary power units (3-30/kW) with a specific power of 150 W/kg and a power density of 170 W/L by 2010.

3.4.2 Technical Approach

Fuel Cell activities will focus on achieving the objectives outlined above by focusing on the polymer electrolyte membrane (PEM) fuel cell because of its low-temperature operation and capability for fast start up. Solid-oxide fuel cells can operate more readily on diesel fuel but require more time and energy for start-up. Figure 3.4.1 shows an example of a fuel cell powered car. Therefore, they are better suited for heavy vehicle applications, such as auxiliary power units (APUs), than for light-duty trucks and automobiles where the duty cycle is typically lower. Direct-methanol fuel cells may simplify fuel cell system design by eliminating the need for on-board hydrogen storage or fuel processing, but they are currently more costly because of high precious metal loading and low power density. Solid-oxide and direct-methanol fuel cell technologies will require greater research and development (R&D) efforts to meet light-duty propulsion requirements. Portable power sources, including direct-methanol fuel cells, are expected to be the first commercial applications of PEM fuel cell technology because of their low power requirements and less stringent cost targets. Stationary fuel cell applications are also expected to begin commercialization in the near term. The manufacturing capability that develops for portable power and stationary fuel cells will help accelerate commercialization of fuel cells for other applications.

Figure 3.4.1 Hybrid Fuel Cell/ Battery-Powered Ford Focus

The Fuel Cell program element will focus on overcoming critical technology barriers, with particular emphasis on achieving high efficiency, durability, and low materials and manufacturing costs. Program objectives will be accomplished through R&D on materials and components as well as on high-volume manufacturing processes for fuel cells, fuel processors, and balance-of-plant components such as air compressors, sensors, and controls. The focus of the program has shifted from developing integrated systems to R&D on materials, components, and enabling technologies for fuel cell power systems operating on hydrogen or reformate from fuels such as methanol, ethanol, natural gas, and gasoline (see Figure 3.4.2).

Because the fueling infrastructure is established for hydrocarbon fuels such as gasoline, propane, and natural gas, fuel processing technology is being developed for both transportation and stationary applications. For transportation, on-board fuel-flexible fuel processing R&D is pursued with gasoline as a benchmark fuel. The primary limitation of on-board fuel processing systems is the long start up time. Thus, the program includes R&D on quick start up reformers. Ongoing research in industry and national laboratories will focus on improved catalysts and engineering efforts aimed at improving the thermal properties of the fuel processor. Successful optimization and integration of the balance-of-plant can also contribute to a shorter start up time. For stationary applications, natural gas and propane are processed for fuel cell systems.

The off-board hydrogen infrastructure pathway will focus on developing and validating technologies to enable the creation of a hydrogen infrastructure. Some of the technologies developed for stationary fuel cell applications such as low-cost, compact fuel processors could also be used for off-board processing of fuels to produce hydrogen at vehicle refueling stations (see Sections 3.1 and 3.2).

The development of new materials for improved fuel cell stack and system performance and for lower cost is central to achieving objectives of the DOE effort. Work is ongoing in universities, national laboratories, and industry to identify new materials and fabrication methods for fuel cell membranes, catalysts, and bipolar plates; and to integrate these new materials and methods into fuel cells for testing. Development of enabling technologies has been a success story for the DOE's Office of Energy Efficiency and Renewable Energy (EERE) programs. The program is progressing by: developing new membranes for operation at temperatures higher than 120°C for improved thermal management and impurity tolerance; developing advanced catalyst-coated membranes; developing highly conductive, gas-impermeable bipolar plates and fabrication processes; minimizing precious-metal loading; and assessing and improving component durability.

Extensive testing of such components in harsh environments and critical analysis of component success or failure, including component modeling, feeds into development of components. The dissemination of components to stack and system manufacturers and to national laboratory test beds for validation is the final component of the hierarchal flow. In addition, several aspects of the program address high-volume manufacturing of fuel cell stack components.

Fuel cell R&D will taper and conclude as technical targets are achieved and commercialization is successful. Once the major cost milestones for stationary and transportation applications are met, R&D for those areas will end.   If specific performance issues remain at that time, R&D could be extended assuming the risk of continued effort is justified by the potential benefit.

Figure 3.4.2 Off Board and On-Board Fuel Processing
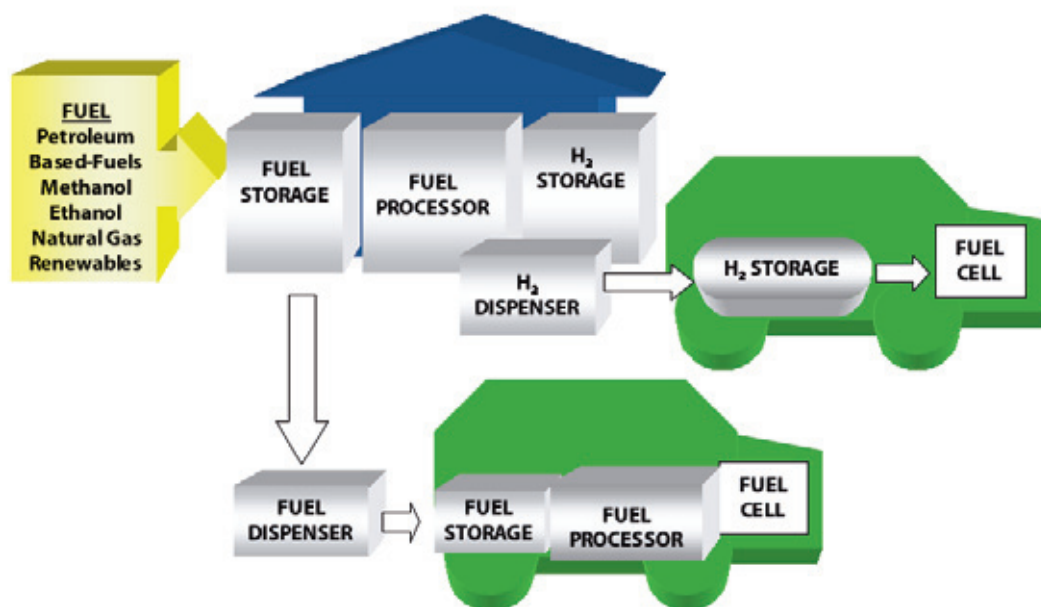
3.4.3 Programmatic Status

Programmatic and technology status is reported each year in the Annual Progress Report for the Hydrogen, Fuel Cells & Infrastructure Technologies Program. These reports address recent, broad programmatic issues and report on progress against the technical barriers and R&D tasks identified in this plan.

Current Activities

Table 3.4.1 summarizes the current activities of the Fuel Cells program element.

Table 3.4.1. Current Fuel Cell Activities		
Challenge	**Approach**	**Activities**
Transportation Systems		
Efficient, cost-effective compressor / expander technologies	• Develop lubricant-free systems • Research and develop new engineering approaches to compressor/expander technologies • Improve efficiencies and performance • Reduce weight and cost	• **UTC Fuel Cells:** Investigating cathode air blower and FPS air blowers with regenerative and centrifugal designs for ambient fuel cell systems. • **TIAX:** Hybrid turbo-scroll compressor/expander modules • **Mechanology:** Toroidal intersecting vane compressor/expander module • **Honeywell:** Developing turbo compressor for operation in PEM-FC transportation systems
Effective, reliable physical and chemical sensors	• Develop accurate, responsive sensors to measure physical properties and chemical species. • Improve mass air flow measurements • Advance humidity detection technology • Enhance temperature sensing • Reduce cost and footprint	• **Honeywell:** Determine customer sensor requirements and develop requisite sensor technology • **UTC Fuel Cells:** Development of physical and chemical sensor technology
Market barriers and analysis	• Assess potential for cost reductions to reach customer-acceptable levels • Evaluate the availability and potential market demand for raw materials • Appraise the ability for fuel cell technology to compete	• **TIAX:** Studying worldwide platinum supply and demand, the potential uses of fuel cells and their associated costs, and fuel choice • **Argonne National Laboratory:** Comparing various transportation technologies and the feasibility of fuel cell vehicles, including well- to wheel efficiencies • **National Renewable Energy Laboratory:** FCV system analysis on trade-offs and optimization • **Breakthrough Technologies Institute:** Determine world-wide status in FCV technology
Stationary Systems		

High-temperature membranes for stationary applications	• Development of high-temperature membranes to facilitate combined heat and power applications and meeting 40,000 durability requirement	• **Fuel Cell Energy:** High-temperature membranes for ambient pressure stationary PEM applications capable of 120°C operation and 40,000-hour durability
Alternative fuel powered fuel cell systems	• Investigating integrated ethanol-fueled fuel cell system	• **Caterpillar:** With subcontractor Nuvera, developing an ethanol fueled stationary system for durability demonstration
Challenge	**Approach**	**Activities**
Fuel Processors		
Distributed natural gas-fueled	• Develop autothermal technology for distributed hydrogen production	• **GE Energy & Environmental Research Corporation:** Developing a natural gas fueled autothermal fuel processor for localized hydrogen production at service stations
Additional research in building fuel cell systems will begin in late 2003 as a result of spring 2003 solicitation.		
Efficient fuel-flexible fuel processors	• Reduce cost, weight, and size • Simplify systems and improve efficiency • Reduce start-up power requirements and time • Decrease the presence of contaminants in the output stream • Improve output capacity	• Nuvera: Developing "STAR" and "HiQ" fuel processing technologies • UTRC: Integrated Pd membrane water-gas shift reactor • Catalytica: New catalyst, plate-based reactor for gasoline steam reforming • University of Michigan: Microchannel fuel processing • Ohio State University: Novel membrane water-gas-shift process • Argonne National Laboratory: Developing fast start fuel processing technology and catalyst research • Pacific Northwest National Laboratory: Microchannel reforming technology • Los Alamos National Laboratory: Fuels effects studies and preferential oxidation

Stack Components		
Low-cost membrane electrode assemblies (MEAs) and high temperature membranes	• Develop new, lower-cost, longer-life materials • Investigating new MEA configurations and low cost catalysis • Improve water and thermal management of systems • Determine fuel/air contaminant thresholds • High volume manufacturing technology	• **3M:** Advanced MEAs for 120ºC+ operation and low cost manufacturing methods • **Southwest Research Institute (w/W.L.Gore):** High-volume electrode production • **DeNora/Dupont:** New cathode alloys, high temperature MEAs with improved kinetics • **UTC Fuel Cells:** High temperature membranes w/ improved kinetics and CO tolerance • **Superior Micropowders:** Low platinum loading technology for MEAs • **Los Alamos National Laboratory:** High temperature membranes and electrode technologies • **Argonne National Laboratory:** High temperature membrane technology
Portable Power/APU's		
Contracts will be awarded through a solicitation in late 2003.		

National laboratories and universities are conducting R&D that cross-cuts these applications and activities. This R&D focuses on advanced concepts and enabling technologies such as high-temperature membranes, improved cathode catalysts, carbon monoxide-tolerant catalysts, low-temperature catalytic fuel processing, water-gas shift catalysts, microchannel heat exchangers, fast-start fuel processing technology, components for direct-methanol fuel cells, benchmarking technology status, and sensors. State-of-the-art fuel-flexible fuel processors are being used at national laboratories to evaluate the effects of fuel composition on fuel cell and fuel processor performance.

3.4.4 Technical Challenges

Cost and durability are the major challenges to fuel cell commercialization. However, hurdles vary according to the application in which the technology is employed. Size, weight, and thermal and water management are barriers to the commercialization of fuel cell technology. In transportation applications, these technologies face more stringent cost and durability hurdles. In stationary power applications, where cogeneration of heat and power is desired, use of PEM fuel cells would benefit from raising operating temperatures to increase performance.

Transportation Propulsion Systems

The cost of fuel cell power systems must be reduced before they can be competitive with internal combustion engine (ICE) technology. Currently the costs for automotive ICE power plants are about $25–$35/kW; a fuel cell system needs to cost $30/kW for the technology to be competitive.

The durability of fuel cell systems has not been established. Fuel cell power systems will be required to achieve the same level of durability and reliability of current automotive engines, i.e., 5,000-hour lifespan (150,000-miles equivalent), and the ability to function over the full range of vehicle operating conditions (-40° to 80° C).

Lightweight, compact on-board hydrogen storage systems and economically viable hydrogen production and delivery also present challenges (see Sections 3.1.3 and 2.2.3).

Air management for fuel cell systems is a challenge because today's compressor technologies are not suitable for automotive fuel cell applications. In addition, thermal and water management for fuel cells are issues because the small difference between the operating and ambient temperatures necessitates large heat exchangers.

Finally, the size and weight of current fuel cell systems must be further reduced to meet the packaging requirements for automobiles. This applies not only to the fuel cell stack, but also to the ancillary components and major subsystems (e.g., fuel processor, compressor/expander, and sensors) making up the balance of power system.

Stationary/Distributed Generation Systems

Stationary applications for fuel cell power systems share many of the technical barriers facing fuel cell power systems for transportation, even though the specific performance requirements for these applications vary considerably. The cost of stationary fuel cell power systems must also be reduced to be competitive with conventional technologies. Stationary systems, however, have an acceptable price point considerably higher than transportation systems ($400–$750/kW for widespread commercialization and as much as $1000/kW for initial applications).

The durability and reliability of fuel cell power systems for stationary applications for more than a few thousand hours also remains to be demonstrated. For stationary applications, more than 40,000 hours of reliable operation in a temperature at -35° to 40°C will be required for market acceptance.
The low operating temperature of PEM fuel cells limits the amount of heat that can be effectively utilized in combined heat and power (CHP) applications. Technologies need to be developed that will allow higher operating temperatures and/or more effective heat recovery systems and improved system designs that will enable CHP efficiencies exceeding 80%. Technologies that allow cooling to be provided from the low heat rejected from stationary fuel cell systems (such as through regenerating dessiccants in a desiccant cooling cycle) also need to be evaluated.

Power electronics and energy management strategies are required that will enable PEM fuel cell power systems in stationary applications to efficiently and cost-effectively manage power transients. This applies to systems intended to operate in a grid-independent mode where the fuel cell system must respond to changing loads in less than 3 milliseconds.

Startup time is a barrier for stationary fuel cell systems in backup power applications. Hybrid systems or other viable methods to address startup time must be developed.

Portable Power Systems

Technical issues unique to fuel cell power systems for consumer electronics include: system and component miniaturization; small-scale fuel processing; microcompressors; fuel storage, distribution, and recharging, especially for low-power applications; and system integration and packaging. Passive operation at near-ambient conditions and insensitivity to orientation are necessary for the low-power applications. Fuel delivery and storage, as well as safety, codes, and standards, are important for consumer electronics and APU systems.

3.4.4.1 Technical Targets

Tables 3.4.2 through 3.4.5 list the DOE technical targets for integrated fuel cell power systems running on hydrogen and gasoline (gasoline is a benchmark fuel), and transportation PEM fuel cell stack systems and fuel-flexible fuel processors running on hydrogen-containing fuel from a fuel processor.. Targets for 2010 are R&D milestones for measuring progress, not necessarily the targets required for successful commercialization of the technology.

Table 3.4.6 lists the DOE technical targets for integrated stationary PEMFC power systems operating on natural gas or propane as benchmark fuels. The targets have been developed with input from developers of stationary fuel cell power systems, and have been established for small (3–25 kW) and large (50–250 kW) power levels. The targets assume a sulfur level in the natural gas or propane of less than 6 ppm sulfur (average value).

Tables 3.4.7 and 3.4.8 list the DOE technical targets for consumer electronics, APUs, and truck refrigeration. Tables 3.4.9 and 3.4.10 list DOE technical targets for automotive sensors and compressor/expander units.

Table 3.4.2. Technical Targets: 50-kWe (net) Integrated Fuel Cell Power Systems Operating on Direct Hydrogen[a]

All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2003 status	2005	2010
Energy efficiency[b] @ 25% of rated power	%	59	60	60
Energy efficiency @ rated power	%	50	50	50

Power density
  excluding H_2 storage
  including H_2 storage
	W/L
	W/L
		400
		TBD
			500
			150
				650
				220

Specific power
  excluding H_2 storage
  including H_2 storage
	W/kg
	W/kg
		400
		TBD
			500
			250
				650
				325

Cost[c] (including H_2 storage)	$/kWe	200	125	45
Transient response (time from 10% to 90% of rated power)	sec	3	2	1

Cold start-up time to maximum power
  @−20°C ambient temperature
  @+20°C ambient temperature
	sec
	sec
		120
		60
			60
			30
				30
				15

Emissions		Zero	Zero	Zero
Durability[d]	hours	1000	2000[e]	5000[f]
Survivability[g]	°C	−20	−30	−40

[a]Targets are based on hydrogen storage in an aerodynamic 2500-lb vehicle and are being updated for compatibility with newly developed hydrogen storage targets.
[b]Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).
[c]Includes projected cost advantage of high-volume production (500,000 units per year).
[d]Performance targets must be achieved at the end of the durability time period.
[e]Includes thermal cycling.
[f]Includes thermal and realistic drive cycles.
[g]Achieve performance targets at 8-hour cold-soak at temperature.

Table 3.4.3. Technical Targets: 50-kWe (net) Integrated Fuel Cell Power Systems Operating on Tier 2 Gasoline Containing 30 ppm Sulfur, Average

(Including fuel processor, stack, ancilliaries)
(Excluding gasoline tank and vehicle traction electronics)
All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2003 status	2005	2010
Energy efficiency[a] @ 25% of rated power	%	34	40	45
Energy efficiency @ rated power	%	31	33	35
Power density	W/L	140	250	325
Specific power	W/kg	140	250	325
Cost[b]	$/kWe	300	125	45
Transient response (time from 10 to 90% power)	sec	15	5	1

Cold startup time to rated power
    @−20°C ambient temperature
    @+20°C ambient temperature
	min
	min
		TBD
		<10
			2
			1
				1
				<0.5

Survivability[c]	°C	TBD	−30	−40
Emissions[d]		<Tier 2 Bin 5[e]	<Tier 2 Bin 5[e]	<Tier 2 Bin 5[e]
Durability[f]	hours	1000[g]	2000[h]	5000[i]
Greenhouse Gases	One-third reduction compared with conventional SI-IC engines in similar type vehicles			

[a]Ratio of direct current (dc) output energy to the lower heating value of the input fuel (gasoline).
[b]Includes projected cost advantage of high-volume production (500,000 units per year) and includes cost for assembling/ integrating the fuel cell system and fuel processor.
[c]Achieve performance targets at 8-hour cold-soak at temperature.
[d]Emissions levels will comply with emissions regulations projected to be in place when the technology is available for market introduction.
[e] 0.07 NO_x g/mile and 0.01 PM g/mile.
[f]Performance targets must be achieved at the end of the durability time period.
[g]Continuous operation.
[h]Includes thermal cycling.
 [i]Includes thermal and realistic drive cycles.

Table 3.4.4. Technical Targets: Fuel Cell Stack Systems Operating on Hydrogen-Containing Fuel from a Fuel Processor (Gasoline Reformate) in 50-kWe (net) Fuel Cell Systems

(Excludes fuel processing/delivery system)
(Includes fuel cell ancillaries: thermal, water, air management systems)
All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2003 status	2005	2010
Stack system power density^{a,b}	W/L	200	400	550
Stack system specific power	W/kg	200	400	550
Stack system efficiency^{c} @ 25% of rated power	%	45	50	55
Stack system efficiency^{c} @ rated power	%	40	42	44
Precious metal loading^{d}	g/rated kW	<2.0	0.6	0.2
Cost^{e}	$/kWe	200	100	35
Durability^{f}	hours	>2000^{g}	>2000^{h}	>5000^{i}
Transient response (time for 10% – 90% of rated power)	sec	<3	2	1
Cold startup time to rated power @ –20°C ambient temperature @ +20°C ambient temperature	min min	2 <1	1 0.5	0.5 0.25
Survivability^{j}	°C	–40	–30	–40
CO tolerance^{k} steady state (with 2% maximum air bleed) transient	ppm ppm	50 100	500 500	500 1000

^{a} Power refers to net power (i.e., stack power minus auxiliary power requirements).

^{b} Volume is "box" volume, including dead space, and is defined as the water-displaced volume times 1.5 (packaging factor). Power density includes ancillaries (sensors, controllers, electronics, radiator, compressor, expander, and air, thermal and water management) for stand-alone operation.

^{c} Ratio of output DC energy to lower heating value of hydrogen-rich fuel stream (includes converter for 300 V bus); ratio of rated power to 25% of rated power efficiencies unchanged, assuming continued proportional reduction in stack efficiency at higher current and proportional increase in compressor efficiency at higher flow rates.

^{d} Equivalent total precious metal loading (anode + cathode): 0.1 mg/cm^2 by 2010 at rated power. Precious metal target based on cost target of <$3/kWe precious metals in MEA [@$450/troy ounce ($15/g), <0.2 g/kWe]

^{e} High-volume production: 500,000 units per year.

^{f} Performance targets must be achieved at the conclusion of the durability period; durability includes tolerance to CO, H$_2$S and NH$_3$ impurities.

^{g} Continuous operation (pertains to full power spectrum).

^{h} Includes thermal cycling.

^{I} Includes thermal and realistic driving cycles.

^{j} Performance targets must be achieved at the end of 8-hour cold-soak at temperature.

^{k} CO tolerance requirements assume capability of fuel processor to reduce CO. Targets for the stack CO tolerance are subject to trade-offs between reducing CO in the fuel processor and enhancing CO tolerance in the stack. It is assumed that H$_2$S is removed in the fuel processor.

Table 3.4.5. Technical Targets: Fuel-Flexible Fuel Processors[a] to Generate Hydrogen-Containing Fuel Gas from Reformulated Gasoline Containing 30 ppm Sulfur, Average for 50-kWe (net) Fuel Cell Systems

(Excludes fuel storage; includes controls, shift reactors, CO cleanup, heat exchangers)
All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2003 status	2005	2010
Energy efficiency[b]	%	78	78	80
Power density	W/L	700	700	800
Specific power	W/kg	600	700	800
Cost[c]	$/kWe	65	25	10

Cold startup time to maximum power
  @ −20°C ambient temperature
  @ +20°C ambient temperature
	min
	min
		TBD
		<10
			2.0
			<1
				1.0
				<0.5

Transient response (time for 10% to 90% power)	sec	15	5	1
Emissions[d]		<Tier 2 Bin 5	<Tier 2 Bin 5	<Tier 2 Bin 5
Durability[e]	hours	2000[f]	4000[g]	5000[h]
Survivability[i]	°C	TBD	−30	−40

CO content in product stream[j]
  steady state
  Transient
	ppm
	ppm
		10
		100
			10
			100
				10
				100

H_2S content in product stream	ppb	<200	<50	<10
NH_3 content in product stream	ppm	<10	<0.5	<0.1

[a]With catalyst system suitable for use in vehicles.
[b]Fuel processor efficiency = total fuel cell system efficiency/fuel cell stack system efficiency, where total fuel cell system efficiency accounts for thermal integration. For purposes of testing fuel-processor-only systems, the efficiency can be estimated by measuring the derated heating value efficiency (lower heating value of $H_2 \times 0.95$/ lower heating value of the fuel in) where the derating factor represents parasitic system power losses attributable to the fuel processor.
[c]High-volume production: 500,000 units per year.
[d]0.07 g/mile NO_x and 0.01 g/mile PM (particulate matter).
[e]Time between catalyst and major component replacement; performance targets must be achieved at the end of the durability period.
[f]Continuous operation.
[g]Includes thermal cycling.
[h]Includes thermal and realistic driving cycles.
[i]Performance targets must be achieved at the end of an 8-hour cold-soak at specified temperature.
[j]Dependent on stack development (CO tolerance) progress.

Table 3.4.6. Technical Targets: Integrated Stationary PEMFC Power Systems Operating onNatural Gas or Propane Containing 6 ppm Sulfur[a], Average

(including fuel processor, stack, and all ancilliaries)
All targets must be achieved simultaneously

Characteristics	Units	Small (3–25 kW) Systems Calendar Year			Large (50–250 kW) Systems Calendar Year		
		2003 Status	2005	2010	2003 Status	2005	2010
Electrical Energy Efficiency[b] @ rated power	%	30	32	35	30	32	40
CHP Energy Efficiency[c] @ rated power	%	70	75	80	70	75	80
Cost[d]	$/kWe	3000	1500	1000	2500	1250	750
Transient Response (time from 10% to 90% power)	msec	< 3	< 3	< 3	< 3	< 3	< 3
Cold Start-up Time to rated power @ -20°C ambient @+20°C ambient	min min	<15 <10	<10 <5	<5 <1	<20 <10	<15 <5	<10 <2
Survivability (min and max ambient temperature)	°C	-25 +40	-30 +40	-35 +40	-25 +40	-30 +40	-35 +40
Durability @ <10% rated power degradation	hour	>6,000	30,000	40,000	15,000	30,000	40,000
Noise	dB	<70 dBA @ 1 m	<65 dBA @ 1 m	<60 dBA @ 1 m	<65 dBA @ 10 m	<60 dBA @ 10 m	<55 dBA @ 10 m
Emissions Combined NO_x, CO, SO_x, Hydrocarbon, Particulates	g/1000 kWh	<15	<10	<9	<8	<2	<1.5

[a] Table assumes average sulfur content in fuels.
[b] Ratio of dc output energy to the LHV of the input fuel (natural gas or propane) average value at rated power over life of power plant.
[c] Ratio of dc output energy plus recovered thermal energy to the LHV of the input fuel (natural gas or propane) average value at rated power over life of power plant
[d] Includes projected cost advantage of high-volume production, entry level production 200 power plants per year, and 2010 production 5000 power plants per year.

Table 3.4.7. Technical Targets: Consumer Electronics (sub-Watt to 50-Watt)[a]

Characteristics	Units	Calendar year		
		2003 status	2006	2010
Specific Power	W/kg	unavailable	30	100
Power Density	W/L		30	100
Energy Density	W-h/L		500	1,000
Cost	$/W		5	3
Lifetime	hours		1,000	5,000

[a]Few sub-watt to 50-watt fuel cell systems exist and it is premature to specify current status.

Table 3.4.8. Technical Targets: Auxiliary Power Units (3–5 kW avg., 5–10 kW peak) and Truck Refrigeration Units (10–30kW)

Parameter	Units	2003[a] status	2006	2010
Specific Power	W/kg	50 [b]	80	150
Power Density	W/L	50 [b]	80	170
Efficiency @ Rated Power[c]	%LHV	20	25	35
Cost	$/kWe	>2,000	$1,500	$400
Cycle Capability (from cold start) over operating lifetime	number of cycles	10	20	500
Durability	hours	100	1,000	5,000 [d]
Start-up Time		2-3 hours	30-45 minutes	15-30 minutes

[a] Estimate of current capability based on cell and small stack laboratory developments.
[b] Without power conditioning.
[c] Durability for light-duty vehicles (LDVs) is 5,000 hours and 15,000 hours for heavy-duty vehicles; the 15,000 hour durability for heavy-duty vehicles (HDVs) is targeted for 2015.
[d] Electrical efficiency only—does not include any efficiency aspects of the heating or cooling likely being provided.

Table 3.4.9. Technical Targets: Sensors for Automotive Fuel Cell Systems[a]	
Sensor	**Requirement**

Carbon Monoxide	(a) 1–100 ppm reformate pre-stack sensor
	  • Operational temperature: <150°C
	  • Response time: 0.1–1 sec
	  • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure
	  • Accuracy: 1%–10% full scale
	
	(b) 100–1000 ppm CO sensors
	  • Operational temperature: 250°C
	  •Response time: 0.1–1 sec
	  • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure
	  • Accuracy: 1%–10% full scale
	
	(c) 0.1–2% CO sensor 250°–800°C
	  • Operational temperature: 250°–800°C
	  • Response time: 0.1–1 sec
	  • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure
	  • Accuracy: 1%–10% full scale

Hydrogen in fuel processor output	• Measurement range: 1%–100% • Operating temperature: 70°–150°C • Response time: 0.1–1 sec for 90% response to step change • Gas environment: 1–3 atm total pressure, 10–30 mol% water, 30%–75% total H_2, CO_2, N_2 • Accuracy: 1%–10% full scale
Hydrogen in ambient air (safety sensor)	• Measurement range: 0.1–10% • Temperature range: –30°–80°C • Response time: under 1 sec • Accuracy: 5% • Gas environment: ambient air, 10%–98% RH range • Lifetime: 5 years • Interference resistant (e.g., hydrocarbons)
Sulfur compounds (H_2S, SO_2, organic sulfur)	• Operating temperature: up to 400°C • Measurement range: 0.05–0.5 ppm • Response time: <1 min at 0.05 ppm • Gas environment: H_2, CO, CO_2, hydrocarbons, water vapor
Flow rate of fuel processor output	• Flow rate range: 30–300 std L/min • Temperature: 80°C • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure

Ammonia	• Operating temperature: 70–150°C • Measurement range: 1–10 ppm • Selectivity: <1 ppm from matrix gases • Lifetime: 5–10 years • Response time: seconds • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Temperature	• Operating range: –40°–150°C • Response time: in the –40°–100°C range <0.5 sec with 1.5% accuracy; in the 100°–150°C range, a response time <1 sec with 2% accuracy • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure • Insensitive to flow velocity
Relative humidity for cathode and anode gas streams	• Operating temperature: 30°–110°C • Relative humidity: 20%–100% • Accuracy: 1% • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm

Oxygen in fuel processor and at cathode exit	(a) Oxygen sensors for fuel processor reactor control
	  • Operating temperature: 200°–800°C
	  • Measurement range: 0%–20% O_2
	  • Response time: <0.5 sec
	  • Accuracy: 2% of full scale
	  • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm
	
	(b) Oxygen sensors at the cathode exit
	  • Measurement range: 0%–50% O_2
	  • Operating temperature: 30°–110°C
	  • Response time: <0.5 sec
	  • Accuracy: 1% of full scale
	  • Gas environment: H_2, CO_2, N_2, H_2O at 1–3 atm total pressure

Differential pressure in fuel cell stack	• Range: 0–1 psi or (0–10 or 1–3 psi, depending on the design of the fuel cell system) • Temperature range: 30°–100°C • Survivability: –40°C • Response time: <1 sec • Accuracy: 1% of full scale • Size: ≤1 in², usable in any orientation • Other: Withstand and measure liquid and gas phases

[a]Sensors must conform to size, weight, and cost constraints of automotive applications.

Table 3.4.10. Technical Targets: Compressor/Expanders (C/E) for Transportation Fuel Cell Systems[a]

Characteristic	Units	2003 Status	2005 Target	2010 Target
Input Power[b] at Full Load				
50-kW$_e$ Unit	kW$_e$	7.0	5.0	5.0
80-kW$_e$ Unit-Reformate/Air	kW$_e$	–	–	4.7
80-kW$_e$ Unit-Hydrogen/Air with Expander	kW$_e$	–	–	4.1
80-kW$_e$ Unit-Hydrogen/Air without Expander	kW$_e$	–	–	13
160-kW$_e$ Unit-Hydrogen/Air with Expander	kW$_e$	–	–	8.3
160-kW$_e$ Unit-Hydrogen/Air without Expander	kW$_e$	–	–	26
Efficiency at Full Flow				
50-kW$_e$ Unit-Compressor	%	<70	80	80
50-kW$_e$ Unit-Expander	%	<80	80	80
80-kW$_e$ Unit-Reformate/Air-Compressor	%	–	–	80
80-kW$_e$ Unit-Reformate/Air-Expander	%	–	–	80
80-kW$_e$ Unit-Hydrogen/Air-Compressor	%	–	–	80
80-kW$_e$ Unit-Hydrogen/Air-Expander	%	–	–	80
160-kW$_e$ Unit-Hydrogen/Air-Compressor	%	–	–	80
160-kW$_e$ Unit-Hydrogen/Air-Expander	%	–	–	80
Efficiency @ 20%-25% of Full Flow[c]				
50-kW$_e$ Unit-Compressor at 1.3 PR (25%flow)	%	<70	80	80
50-kW$_e$ Unit-Expander at 1.2 PR (25% flow)	%	25-35	45	45
All other 80-160-kW$_e$ units, reformate/air or H$_2$/air				
Compressor at 1.3 PR, (25% flow)	%	–	–	80
Expander at 1.2 PR, (25% flow)	%	–	–	50
Volume[d]				
50-kW$_e$ unit	L	10-12	8-11	8-11
All other 80-kW$_e$ units, reformate/air or H$_2$/air	L	–	–	15
All other 160-kW$_e$ units, H$_2$/air	L	–	–	25
Weight[d]				
50-kW$_e$ Unit	kg	10-12	8-11	8-11
All other 80-kW$_e$ units, reformate/air or H$_2$/air	kg	–	–	15
All other 160-kW$_e$ units, H$_2$/air	kg	–	–	25
Cost[e]				
50-kW$_e$ Unit	$	600	400	300
80-kW$_e$ units, reformate/air or H$_2$/air	$	–	–	400
All other 160-kW$_e$ units, H$_2$/air	$	–	–	600
Turndown Ratio				
50-kW$_e$ Unit		5	10-15	10-15
All other units		–	15	15
Noise dB(A) at 2 meters				
50-kW$_e$ Unit	dB(A)	>90	70	70
All other units	dB(A)	–	–	70

[a]Targets represent new, unpublished Revised Guidelines for compressor technologies.
[b]Input power to the shaft to power an air system, includes motor/motor controller overall eff. of 85%:
- 50-kWe comp/exp for ref./air flow--76 g/sec (dry) max. flow for compressor, compressor outlet
  pressure is 2.5 atm. Exp. inlet conditions are 82 g/sec (at full flow), 250°C, and 2.1-2.2 atm.
- No 50-kWe compressor/expander or compressor only unit for hydrogen/air flow only is specified.
- 80-kWe comp/exp unit for ref/air flow--115 g/sec (dry) max. flow for comp., comp. outlet
  pressure at 2.5 atm. Exp. inlet conditions assumed to be 120 g/sec (full flow), 250°C, and 2.2 atm.
- 80-kWe comp/exp unit for H2/air flow--87 g/sec (dry) max. flow for comp., outlet pressure is 2.5 atm. Expander
  (if used) inlet conditions assumed at 87 g/sec (at full flow), 80°C, and 2.3 atm.
- 160-kWe comp/exp for H2/air flow----175 g/sec (dry) max. flow for comp., comp. outlet
  pressure is 2.5 atm. Exp. (if used) inlet flow conditions 175 g/sec (full flow), 80°C, and 2.2-2.3 atm.
[c]The pressure ratio is allowed to float as a function of system load/flow rate. The chosen point of operation differs between
CEM units due to their different size and point of optimization.
[d]Weight, volume, and cost include the motor and motor controller for the 50, 80, and 160-kWe units.
[e]Cost targets based on a mfg. volume of 100,000 units per year, includes cost of motor and motor controller.

Note: Targets that have not yet been defined are indicated by –.

3.4.4.2 Barriers

Of the many issues discussed here, cost and efficiency present two of the more significant barriers to the achievement of clean, reliable, cost-effective systems.

Transportation Systems Barriers

A. Compressors/Expanders. Automotive-type compressors/expanders that minimize parasitic power consumption and meet packaging and cost requirements are not available. To validate functionality in laboratory testing, current systems often use off-the-shelf compressors that are not specifically designed for fuel cell applications. These result in systems that are heavy, costly, and inefficient. Automotive-type compressors/expanders that meet the FreedomCAR technical guidelines need to be engineered and integrated with the fuel cell and fuel processor so that the overall system meets packaging, cost, and performance requirements.

B. Sensors. Automotive-type sensors are required that meet performance and cost targets for measuring physical conditions and chemical species in fuel cell systems. Current sensors do not perform within the required ambient and process conditions, do not possess the required accuracy and range, and/or are too costly.

C. Thermal Management. Thermal management processes include heat use, cooling, and steam generation. Current heat exchangers do not adequately accommodate the low temperature differential available for fuel cell system heat rejection. Other advanced heat exchangers and materials are required to achieve the most efficient, cost-effective system.

D. Fuel Cell Power System Benchmarking. The interdependency of fuel cell subsystems is an important consideration in the development of individual components for propulsion and APUs. The interdependency of the system components will affect the packaging, response, and efficiency of the power system. Development of a validated system model and periodic benchmarking of integrated fuel cell power systems, subsystems, and components are required to assess technology status. Ultimately, operation of components and subsystems will be validated in the integrated systems developed outside the program.

Distributed Generation Systems Barriers

E. Durability. To compete against other distributed power generation systems, stationary fuel cells must achieve greater than 40,000 hours durability. Sulfur-tolerant catalysts and membrane materials are required to achieve this durability target, and research must elucidate failure mechanisms. Benchmarking of the state-of-the-art R&D systems is also necessary.

F. Heat Utilization. The low operating temperature of PEM fuel cell system technology limits the use of heat generated by the fuel cell, which represents approximately 50% of the energy supplied by the fuel. More efficient heat recovery systems, improved system designs, and/or higher temperature operation of current systems are needed to utilize the low-grade heat and achieve the most efficient (electrical and thermal) distributed generation power systems.

G. Power Electronics. Distributed generation fuel cell power systems will require energy management strategies and power electronics that enable the fuel cell power system to manage power transients and load following requirements efficiently and cost effectively. Grid interconnection may also be a major commercialization issue for many distributed fuel cell power applications as with all emerging distributed power generation technologies (grid interconnection issues are being addressed by the Office of Distributed Energy and Electric Reliability). Priority power management issues include developing a universal dc buss, high-frequency power conditioner, integrated transfer switch and inverter, and grid-independent electronics.

H. Startup Time. Fuel cell systems take longer to cold start (30 second minimum) compared to other distributed power generation systems, especially backup power systems. R&D to address startup time through the use of hybrid systems or other viable methods is needed.

Fuel-Flexible Fuel Processors Barriers

I. Fuel Processor Startup/Transient Operation. Fuel processors startup slowly and do not respond rapidly to variations in power demand required by automotive and stationary applications. Fuel consumption during this start up period needs to be minimized to compete with conventional ICE technology. Automotive fuel cell power plants will be required to meet rapid startup needs and to follow load variations of typical driving patterns. Improved reactor designs and catalysts with reduced mass are required.

J. Durability. Current fuel processing systems have not achieved required durability. A reason for this is the impurities contained in the fuels entering the reformer. Limited data are available on the effects of fuel composition, additives, fuel blends, impurities (e.g., sulfur) and contaminants on fuel processor catalyst and subsystem component durability. The effect of carbon formation on catalyst activity for various fuels and the effect of operating conditions on durability is not adequately defined. On-board sulfur removal technology and impurity tolerant catalysts and/or removal processes are required.

K. Emissions and Environmental Issues. Data on the effects of fuel/fuel blend properties on the potential formation of toxic emissions are limited. Fuel processor and stack emissions (including evaporative emissions) are not adequately characterized. Standardized emission test procedures are lacking. Startup emissions are not well characterized.

L. Hydrogen Purification/Carbon Monoxide Cleanup. A fuel processor must produce high-quality hydrogen to prevent degradation of the fuel cell stack. Liquid fuels contain

impurities such as sulfur compounds. These compounds and their derivatives, as well as carbon monoxide, must be removed to prevent loss of performance in the fuel cell. To prevent fuel cell catalyst poisoning, the fuel processor needs to deliver a hydrogen stream with CO levels of less than 10 ppm under most operating conditions and a maximum of 100 ppm during transients and startup. Current CO cleanup systems produce a fuel stream with an acceptable CO level under steady-state operation, but require an extensive control system for transient and startup operation. Improved catalysts for preferential oxidation and/or improved membranes for hydrogen separation are needed to meet fuel purity requirements under transient and startup operation.

M. Fuel Processor System Integration and Efficiency. Full-size, fuel-flexible, integrated systems that use improved catalysts and reactors that validate the required operating characteristics and efficiency for automotive applications must be developed. Technical data on the effects of fuel properties on fuel processors are needed.   Current understanding of fuel processor subsystem combustion and chemical processes is inadequate.   Data and models for fuel impacts on fuel processor performance and emissions are limited.   Performance variations for some fuels among various types of fuel processors are not understood.

N. Cost. The cost of fuel processing technology is because the operating temperature requires high-temperature materials, the low activity of shift catalysts requires large reactors, precious metal catalysts must be used, and the complexity of the device requires multiple reactors and thermal integration. Substitution of lower-cost materials (particularly reduced Pt or non-Pt catalysts) and components, and integration of subsystems and functions are required to achieve cost goals.

Component Barriers

O. Stack Material and Manufacturing Cost. Stack material cost/manufacturing (bipolar plates, membrane electrode assemblies, gas diffusion layer) is too high. PEM fuel cell stacks use high-cost bipolar plates, high-cost membranes, and precious metal catalysts (such as Pt). Lower cost, lighter bipolar plates and low-cost, high-performance membranes and catalysts enabling ultra-low loading are required to make fuel cells competitive. Low-cost, high-volume manufacturing processes are also necessary.

P. Durability. Durability of fuel cell stacks, which must include tolerance to impurities and mechanical durability, has not been established. Additional improvements in anode tolerance to carbon monoxide are required to facilitate simplification of the system and to reduce cost and weight. Tolerance to other impurities, such as ammonia and possibly sulfur, is also necessary.

Q. Electrode Performance. Voltage losses at the cathode are too high to meet efficiency targets. Anode and cathode performance depend on precious metal loading, which is currently too high to meet cost targets. In addition, power densities at the higher voltages required for high-efficiency operation are currently too low to meet cost and packaging targets.

R. Thermal and Water Management. Higher temperature membranes (to raise the operating temperature) and/or improved heat utilization, cooling, and humidification techniques are needed. The relatively small difference between the fuel cell stack operating temperature and ambient air temperature is not conducive to conventional heat rejection approaches. Water management techniques to address humidification requirements and maintain water balance are required.

3.4.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.4.11. Concerns regarding safety will be addressed within each task in coordination with the appropriate program element. The duration of a task and the barriers associated with it (see Section 3.4.3) appear after the task title.

Table 3.4.11. Technical Task Descriptions		
Task	**Description**	**Duration/Barriers**
Transportation Systems		
1	**Chemical and Physical System Sensors** Chemical Sensors: Prototype Development Tasks • Measure the CO concentration at three locations: entrance to the fuel cell stack, outlet of the preferential oxider, and outlet of the reformer. • Determine hydrogen concentration at the fuel processor outlet over a wide range of concentrations and temperatures in the presence of other constituents in the reformate stream. • Develop prototype low-cost sensors to monitor ambient concentrations of hydrogen for safety in the presence of other species found in the ambient air. • Measure the concentration of sulfur compounds such as H_2S, SO_2, and organic sulfur compounds in the presence of other reformate constituents. • Measure the concentration of ammonia in high-humidity reformate stream from autothermal reformers in the presence of other constituents. • Develop prototype sensors for fuel processor reactor control and for measuring oxygen concentration at the cathode exit. Physical Sensors: Prototype Development Tasks • Develop prototype flow measuring devices for measuring the flow rate of reformate or hydrogen into the fuel cell at 1–3 atm total pressure. • Develop fast-response temperature sensors that operate in high humidity reformate streams that are insensitive to flow velocity. • Measure the relative humidity ofanode and cathode gas streams.	12 Quarters/Barrier B

2	**Sensors Meeting 2010 Targets** Chemical Sensors: Verification Tasks • Measure the CO concentration at three locations: entrance to the fuel cell stack, outlet of the preferential oxider, and outlet of the reformer. • Determine hydrogen concentration at the fuel processor outlet over a wide range of concentrations and temperatures in the presence of other constituents in the reformate stream. • Verify low-cost sensors to monitor ambient concentrations of hydrogen for safety in the presence of other species found in the ambient air. • Measure the concentration of sulfur compounds such as H_2S, SO_2, and organic sulfur compounds in the presence of other reformate constituents. • Measure the concentration of ammonia in high-humidity reformate stream from autothermal reformers in the presence of other constituents. • Verify sensors for fuel processor reactor control and for measuring oxygen concentration at the cathode exit. Physical Sensors: Verification Tasks • Verify flow measuring devices for measuring the flow rate of reformate or hydrogen into the fuel cell at 1–3 atm total pressure. • Verify fast-response temperature sensors that operate in high humidity reformate streams that are insensitive to flow velocity. • Measure the relative humidity for the anode and cathode gas streams.	20 Quarters/Barrier B

3	**Benchmarking, Hardware Evaluation, and Analyses**
	
	• Test and evaluate fuel cell power systems under simulated automotive drive and rigorous durability cycles.
	• Quantify fuel cell power system emissions.
	• Conduct analyses for:
	    o Overall and specific component costs for transportation fuel cell systems
	    o Availability and cost of platinum group metals
	    o Codes and standards for safety, durability, and reliability for fuel cell power systems for transportation
	    o Reconciliation of well-to-wheels performance, efficiency, emissions, and cost
	    o Fuel choice for fuel cell vehicles (FCVs)
	    o Fuel processing/fuel cell system
		28 Quarters/ Barriers D,K,N,O

4	**Air and Thermal Management** • Develop and test low-cost, high-efficiency, lubrication-free compressors, expanders, motors, motor controllers (turbo, torroidal intersecting vane, hybrid scroll) • Develop and test low-cost, high-efficiency, lubrication-free blowers, motors, motor controllers • Investigate and develop advanced heat rejection technologies and materials (compact humidifiers, heaters, and radiators)	12 Quarters/ Barriers A,C
5	**Compressors Meeting 2010 Guidelines** • Verify advanced compressors/motor/expanders and blowers that meet the 2010 targets for weight, volume, performance and cost.	20 Quarters/Barrier A

Distributed Generation Systems

6	**Distributed Generation and Back-up Power Systems R&D** • Develop stationary fuel cell system that meets the 2005 technical targets for distributed generation systems. • Mitigate technical, commercial, and cost barriers to stationary fuel cells. • Work with DEER and utility partners to address interconnectivity to grid issues. • Develop CHP fuel cell systems to cost-effectively recover thermal energy to meet some or all of the building's heating/cooling requirements. • Develop power systems for back-up or peak shaving applications for commercial/industrial operations. • Verify integrated stationary fuel cell systems. • Identify and understand failure mechanisms to enable improvements in reliability and durability. • Develop energy management strategies that address the ability of the integrated fuel cell system to cost-effectively manage various power loads by optimizing interior and exterior electrical interfaces.	16 Quarters/ Barriers E,F,G,H
7	**Advanced Distributed Energy Fuel Cell System** • Develop a stationary fuel cell system that can operate on natural gas or propane at 40% or higher efficiency. • Develop an advanced stationary fuel cell system that can achieve a cold start up time of less than 1 minute. • Demonstrate through accelerated testing a stationary fuel cell system showing potential to achieve >40,000-hour durability goal.	12 Quarters/ Barriers E,F,G,H
8	**Distributed Generation Fuel Processing** • Develop fuel processing systems that can reform natural gas or propane to hydrogen for stationary applications. • Develop fuel processing systems that meet technical and cost targets for 2005. • Develop advanced water-gas-shift catalysts and reactor designs that meet requirements for operational space velocity.	12 Quarters/ Barriers E,F,G,H,I,J,K,L,M,N

9	**High-Temperature Membranes for Distributed Generation Applications** • Develop highly conducting, high temperature membranes capable of achieving 100°-140°C with improved electrical and mechanical properties. • Demonstrate improved CO tolerance. • Develop lower cost high-temperature membranes. *Note - This task was initiated under the Fuel Cells for Buildings Program (Office of Power Technologies) and feeds into Task 13	6 Quarters/ Barriers E,F,L,P,R
10	**PEMFC Thermal Utilization** • Develop and test improved heat recovery system that improves net system efficiency. • Develop advanced heat exchangers, condensers, and humidifiers. • Improve system humidification to reduce overall energy required to humidify gases while reducing size and cost. • Investigate heat generated cooling (such as desiccant cycles).	12 Quarters/ Barriers C,F,R

Fuel Processors		
11	**Quick-Start Reformer** • Develop a highly efficient integrated (10-50-kW) fuel-flexible fuel processor system that includes reformer, shift reactors, sulfur removal beds, CO cleanup systems, sensors, and controls that meets 2005 technical targets. • Develop a laboratory-scale fuel processor system including all appropriate reactors that minimizes start-up time through innovative reactor design, advanced catalysts and parallel reactor warm-up. • Develop and evaluate water-gas-shift catalysts with improved activity and durability under automotive operating conditions. • Develop and evaluate preferential oxidation systems to reduce CO from the fuel processor stream under steady-state and transient operation. • Develop fuel processing catalysts (reforming, shift, preferential oxidation, desulfurization, etc.) having higher activities, greater stability, lower cost and that enable lower reactor operating temperatures. • Develop compact steam generators, anode tail-gas burners, fuel pre-heaters, and other components that can be integrated into fuel processor systems. • Develop efficient, compact heat exchangers for fuel processor systems. • Develop microchannel and plate reactor fuel processing technology. • Evaluate alternative fuel processing techniques. • Complete testing and evaluation of system performance and emissions on conventional and alternative fuels over steady-state and transient operation. • Develop methods for using waste heat and minimizing heat rejection in the fuel processor. • Verify and improve fuel processor model and system analyses.	8 Quarters/ Barriers I,J,K,L,M,N

12	**Advanced Catalyst/Reactor R&D Meeting 2010 Technical Targets** • Develop a highly efficient quick-start integrated fuel-flexible fuel processor system (10-50-kW) meeting 2010 targets that includes reformer, shift reactors, sulfur removal beds, CO cleanup systems, sensors, and controls. • Establish manufacturing methods for critical fuel processing components. • Improve methods for using waste heat and minimizing heat rejection in the fuel processor. • Test the fuel processor system under automotive drive and rigorous durability cycles. Verify models and analytical tools and test emissions. • Develop and evaluate water-gas-shift catalysts required to meet fuel processor 2010 targets under automotive operating conditions. • Research and develop fuel processing catalysts (reforming, shift, preferential oxidation, desulfurization, etc.) having higher activities, greater stability, lower cost and that enable lower reactor operating temperatures. • Integrate compact steam generators, anode tail-gas burners, fuel pre-heaters, and other components into fuel processor systems. • Develop microscale fuel processing technology. • Evaluate alternative fuel processing techniques. • Verify and improve fuel processor model and system analyses	26 Quarters/ Barriers I,J,K,L,M,N
Stack Components		
13	**High-Temperature Membrane RD&D (See Task 9)** • Investigate new approaches/electrode structures to achieve good adhesion between new membranes and catalyst layer. • Develop proton-conducting fuel cell membranes for operation at 120°C. • Improve understanding of nature of local structure in catalyst layer. • Increase knowledge of proton conduction in high-temperature membrane systems. • Develop membranes with nonaqueous proton-conducting phases for stationary fuel cell membranes for operation at >120°C. • Investigate membranes that can function at low hydration levels. • Fabricate and test MEAs with high-temperature membranes in single cells. • Investigate high temperature membrane/MEA long-term stability and durability. • Verify high-temperature membranes in subscale (5–10 kW) stack.	20 Quarters/ Barriers C,E,F,L,P,Q,R

14	**MEA Materials, Components, Processes** • Investigate and develop low-cost polymer membranes having higher ionic conductivity, improved humidification properties, and lower gas permeability than state-of-the-art membranes. • Develop and test improved gas diffusion layer on full-size cells. • Investigate the effects of sulfur impurities on catalyst performance. • Design, synthesize, and evaluate alternative catalyst formulations and structures (to reduce or eliminate precious metal loading) for carbon monoxide tolerance and oxygen reduction. • Investigate and develop alternative bipolar plate materials/coatings that are low-cost, lightweight, corrosion-resistant, and impermeable. • Fabricate and test MEAs in full-size single cells. • Investigate and develop methods for producing low-cost, high-rate fabrication of fuel cell components (e.g., bipolar plates, membranes, MEAs, and gas diffusion layer). • Verify reproducibility of full-size components produced in high-rate manufacturing processes. • Integrate components in subscale (to 10 kW) stack system to Verify performance, i.e., increased efficiency, power density, and reliability compared with previous development efforts.	8 Quarters/ Barriers O,P,Q
15	**Advanced MEA Meeting 2010 Targets** • Incorporate advanced cathode and membrane in MEA with Pt loading at 2010 targets. • Verify advanced MEA in single cell. • Verify advanced MEA in 5-10 kW stack. • Demonstrate low-cost, high-volume manufacturing processes for advanced MEAs. • Establish durability of advanced MEAs for 2010 targets for transportation and stationary applications.	24 Quarters/ Barriers O,P,Q,R
16	**Direct Methanol Fuel Cells** • Design and test advanced cathode catalysts with low Pt. • Develop reduced methanol crossover membranes and MEAs. • Build and evaluate improved-performance direct-methanol single cell. • Design and build 0.5 kW DMFC stack system with improved power density, efficiency, and water management. • Test and evaluate 0.5 kW DMFC stack. • Develop and test DMFCs for consumer electronic devices.	6 Quarters/ Barriers D,O,Q,R

17	**Auxiliary/Portable Power** • Develop advanced methanol oxidation catalyst, resistant to methanol, and MEAs with low Pt-loading for DMFCs. • Develop miniature fluid handling technologies for DMFC systems. • Develop and demonstrate low-cost, high-volume manufacturing processes for auxiliary/portable power fuel cells. • Develop miniature fuel processors for PEMFC and solid oxide fuel cell (SOFC) systems. • Determine system requirements for fuel cell APUs for HDVs. • Develop and verify fuel cell technologies for APUs (to 30 kW), consumer electronic devices (< 50 W), and off-road systems. • Develop diesel reforming capability for auxiliary power units. • Test and evaluate fuel cell APUs for HDVs under simulated duty and rigorous durability cycles.	13 Quarters/ Barriers D,L,M,O,P,Q
18	**Advanced APUs** • Develop high specific power/power density, high durability, 1–30 kW SOFC systems that meet year 2010 technology targets, provide simplified fuel processing, and which operate at temperatures on the order of 800°C. *Note - This task will be conducted in coordination with the Office of Fossil Energy	16 Quarters/ Barriers D,L,M,O,P,Q

Note: The total duration of the program planning period is 32 quarters; tasks that begin before this period or continue beyond it do not reflect durations outside the planning period.
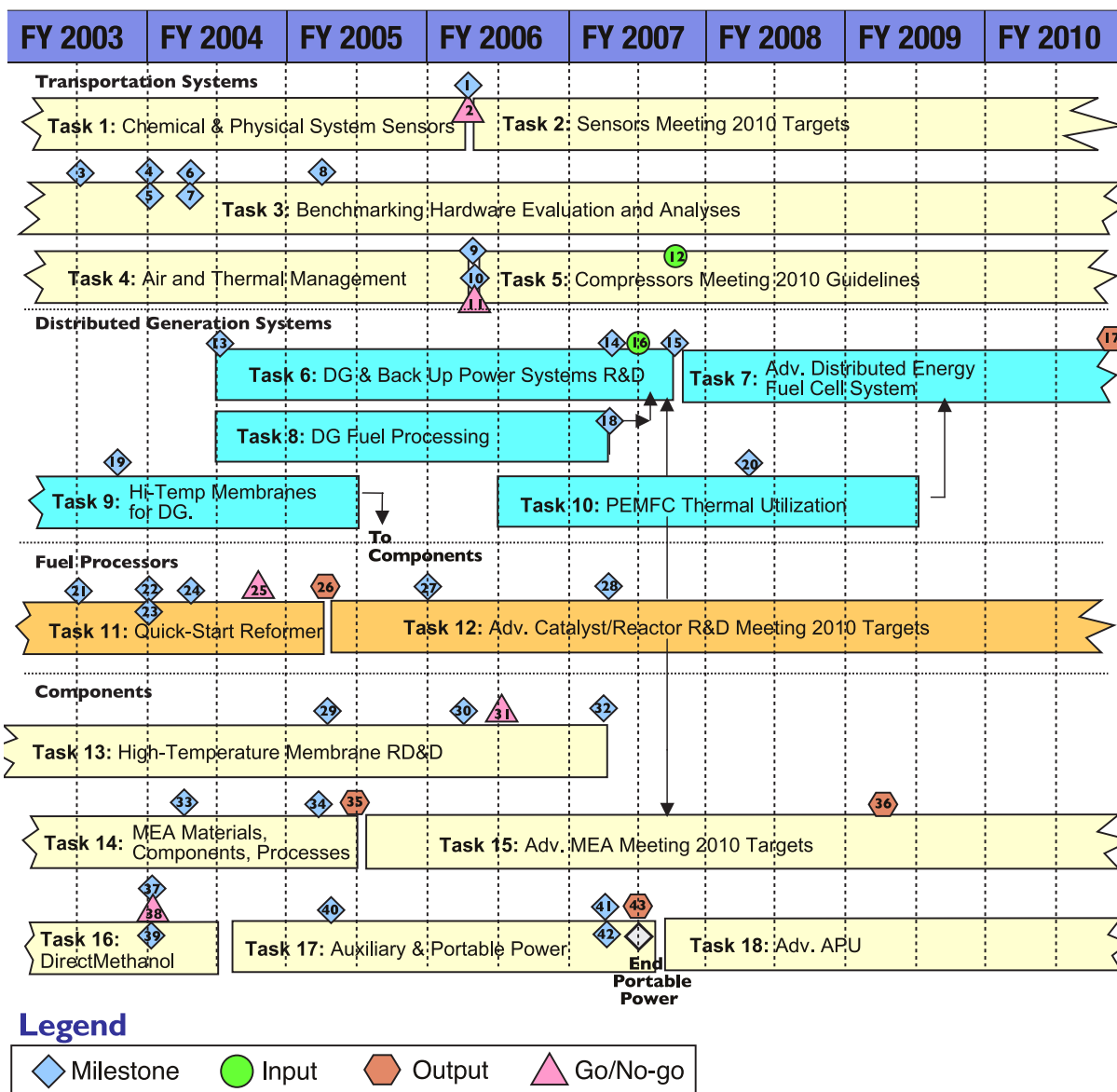

3.4.6 Milestones

Figure 3.4.3 shows the interrelationship of milestone, tasks, supporting inputs, and technology program outputs for the Fuel Cell program element from FY 2004 through FY 2010. This information is also summarized in Table B.4 in Appendix B.

Figure 3.4.3 Hydrogen Education R&D Network

For chart details see next page.

1. Complete development and testing of low-cost, high-sensitivity sensors.
2. Go/No-Go: The status of sensors and controls technologies will be assessed and compared with the established technical and cost targets. Based on the assessment and the degree of success, the technologies will be released for use, more development will be indicated, or effort will be terminated.
3. Deliver critical analysis of well-to-wheels analyses regarding fuel cell system performance, efficiency, greenhouse gas emissions, and cost .
4. Deliver model of FCV system.
5. Quantify fuel cell power systems emissions.
6. Complete initial evaluation of 75-kW advanced integration, atmospheric gasoline reformed system.
7. Complete modeling of the availability and economics of platinum group metals.
8. Complete analysis for overall and specific component costs for transportation fuel cell systems.
9. Complete development and testing of low-cost, high-efficiency, lubrication-free compressors, expanders, blowers, motors, and motor controllers.
10. Complete development of heat rejection technologies (compact humidifiers, heat exchangers, and radiators).
11. Go/No-Go: The status of air management and thermal management technologies will be assessed and compared with the established technical and cost targets. Based on the assessment and the degree of success, the technologies will be released for use, more development will be indicated, or effort will be terminated.
12. Input from Storage: Complex hydride integrated system meeting 2005 targets

13. Complete 4,000-hour test of ethanol-fueled distributed generation system.
14. Demonstrate prototype back up power system.
15. Demonstrate stationary fuel cell system with 35%-40% electrical efficiency.
16. Input from Storage: Full-cycle, integrated chemical hydride system meeting 2005 targets
17. Output to Technology Validation: Stationary PEM Systems with 40,000-hour durability
18. Verify fuel processing subsystem performance for distributed generation to meet system targets for 2010.
19. Demonstrate performance (600 mV at 400 mA/cm2) of an ultra-thin membrane (< 75 µm) in an MEA under atmospheric conditions at 120°C in a 30-cm2 cell.
20. Demonstrate the effective utilization of fuel cell thermal energy for heating to meet combined heat and power (CHP) efficiency targets.

21. Demonstrate fuel-flexible fuel processor meeting year 2005 targets for efficiency, power density, specific power, and emissions. Measure startup capability.
22. Verify quick-start concept in brass-board prototype system demonstrating capability to meet 2010 startup technical target.
23. Verify small scale, microchannel reformer.
24. Fabricate prototype ion transport membrane module.
25. Go/No-Go: Determine whether to continue advanced fuel processing R&D and downselect technology to meet year 2010 technical targets (80% efficiency, 800 W/L, 800 W/kg, <0.5 min startup)
26. Output to Production: Fuel-flexible fuel processor technology
27. Verify low-cost, high-efficiency hydrogen enhancement systems.
28. Verify quick-start concept in brass-board prototype system demonstrating capability to meet all 2010 technical targets.

29. Demonstrate 120°C membrane in MEA/single cell.
30. Demonstrate 120°C MEA in <10 kW stack.
31. Go/No-Go: Demonstrate MEA in single cell meeting 2005 platinum loading and performance targets
32. Verify first generation 150°C membrane in MEA/single cell.
33. Verify reproducibility (physical and performance) of full-size bipolar plates in high-rate manufacturing processes.
34. Verify reproducibility (physical and performance) of full-size MEAs in high-rate manufacturing processes.
35. Output to Technology Validation: Laboratory PEM technology with 2,000 hours durability, $125/kW
36. Output to Technology Validation: Laboratory PEM technology with 5,000 hours durability, $45/kW
37. Identify main routes of DMFC performance degradation.
38. Go/No-Go: Determine whether to continue funding of DMFC R&D for transportation applications
39. Downselect design scenarios for vehicular fuel cell APUs for further study.
40. Complete evaluation of fuel cell systems for APUs.
41. Demonstrate 20-50 W portable power fuel cell system at 30 W/kg, 30 W/L, and $5/W.
42. Verify 3-10 kW APU system at 80 W/kg and 80 W/L.
43. Output to Industry: Portable power PEM technology